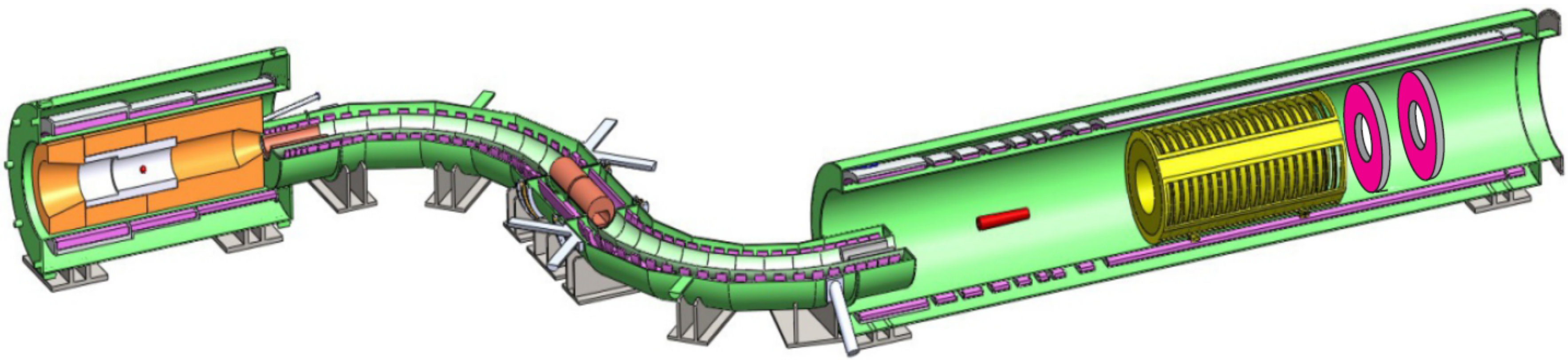
The Mu2e Experiment at Fermilab



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on behalf of Mu2e collaboration

IFAE2014
April 9, 2014

Outline

✓ The search for muon-electron conversion

- Charged Lepton Flavor Violation (cLFV): what is μ conversion?
- Experimental Technique
- Physics backgrounds

✓ The Mu2e experiment layout

- The Solenoids
- Cosmic Rays Veto, Tracker
- Signal Sensitivity

✓ The BaF2 Crystal Calorimeter

What is μe Conversion?

❑ The neutrino-less conversion of a muon to an electron in the field of a nucleus is a particularly interesting example of an LFV process involving charged leptons.

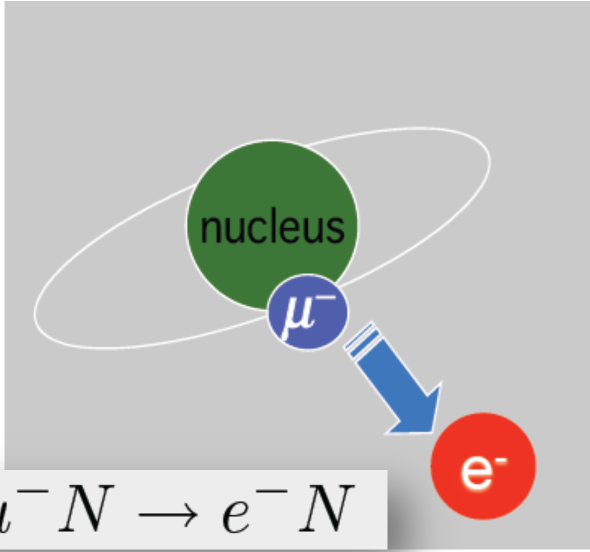
Stop **μ⁻** in atoms: **μ⁻** → **1s** state

1.Capture: $\mu^- N \to \nu_\mu N'$ (60%)

2. Decay: $\mu^- N \to e^- \nu_\mu \bar{\nu}_e$ (40%)

3. Coherent Conversion:

A Single Monoenergetic Electron
If $N = Al$, $E_e = m_\mu - BE = 105.$ MeV



$$\mu^- N \to e^- N$$

❑ In the Standard Model, such conversions would take place through higher order Feynman diagrams involving virtual neutrino mixing, *at a rate far below the threshold of any currently conceivable experiment* .

$$BR_{SM}(\mu^- N \to e^- N) \approx 10^{-56}$$

Beyond the SM

❑ **Any detectable signal would be a definite signature, even if indirect, of new dynamics at very high energy scales.**

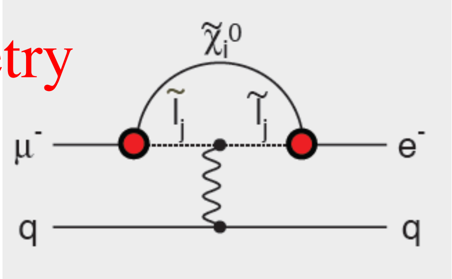
Sensitive to mass scales up to O(10^4 TeV)

❑ Enhanced rate for this decay is an almost universal feature of models beyond the Standard Model, and the fact that such decay has not been observed has constrained or eliminated some of these models.

The Mu2e experiment is designed to search for the signature of a captured muon converting to an electron through the exchange of virtual particles with an Aluminum nucleus:

Supersymmetry

rate ~ 10^{-15}



Experimental Technique

Normalize to Capture:

$$R_{\mu e} = \frac{\Gamma(\mu^- + (A,Z) \to e^- + (A,Z))}{\Gamma(\mu^- + (A,Z) \to \nu_\mu + (A,Z-1))}$$

Al turns into **Mg**

Negatively charged muons that stop in matter are quickly trapped and form muonic atoms:

- The muon cascades to 1s orbital by electromagnetic transitions (**X-rays provide the stop rate**. This rate will be measured with a germanium detector downstream near the beam dump).

After capture,

- Mg → Al by a 2.6 MeV β followed by γ that could be used to measure capture rate**.**

CLFV has actually been seen in California

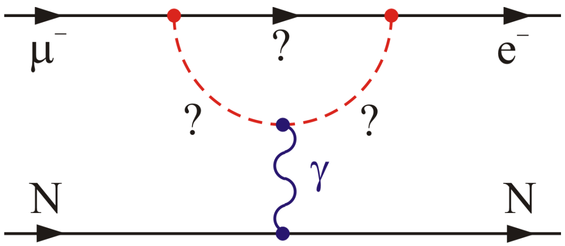
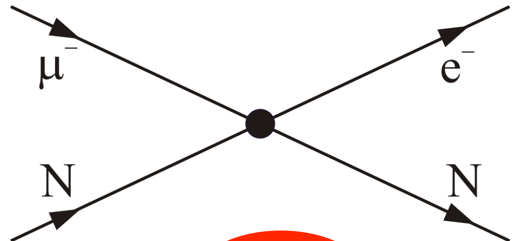
CLFV has actually been seen in California

Mu2e goal

$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z)) \rightarrow e^- + N(A,Z))}{\Gamma(\mu^- + N(A,Z) \rightarrow \text{ all muon capture})} \leq 6 \times 10^{-17} \text{ (@90\%CL)}$$

Mu2e will start data taking at Fermilab in the second half of 2019

Two types of amplitudes contribute

Loops	Contact terms
	
$\mu\to e\gamma$	$\cancel{\mu\to e\gamma}$
$\mu N\to eN$	$\mu N\to eN$
$\mu\to eee$	$\mu\to eee$

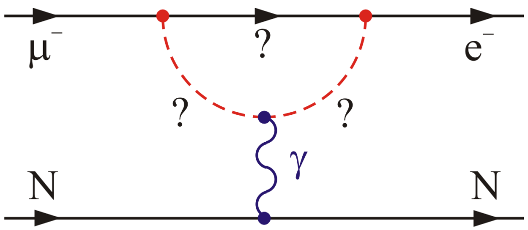
Effective Lagrangian

$$\mathrm{L}_{\mathrm{CLFV}} = \frac{m_\mu}{\boxed{(\kappa+1)}\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\boxed{\kappa}}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)$$

Sensitivity to high mass scales

$$L_{CLFV} = \frac{m_\mu}{\boxed{(\kappa+1)}\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\boxed{\kappa}}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)$$

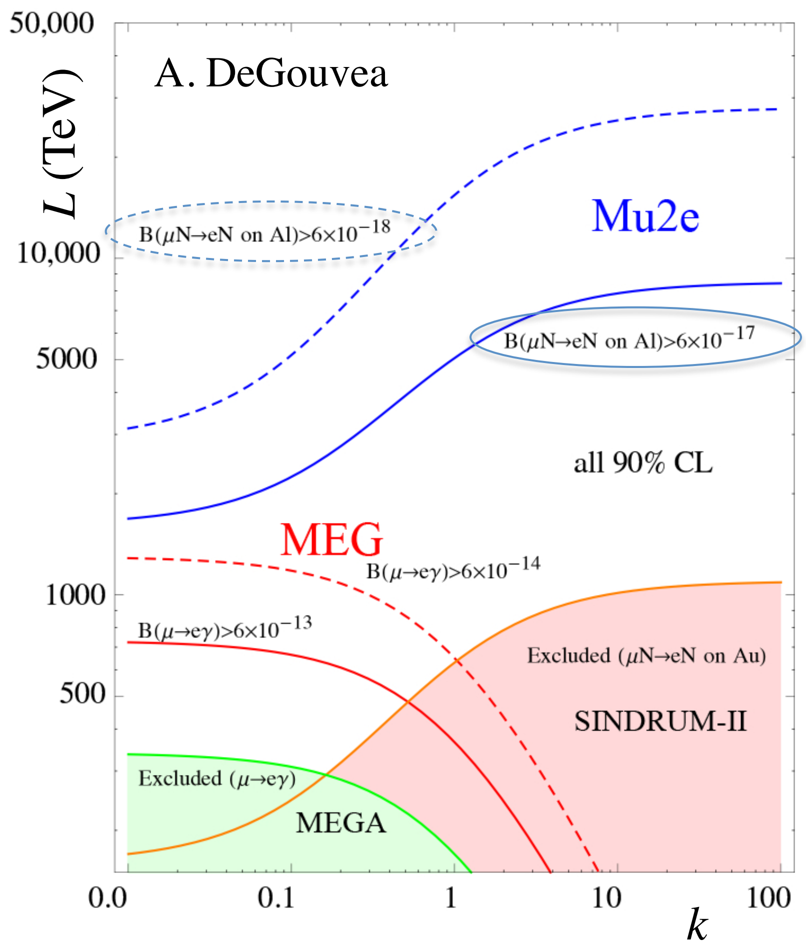
Loops dominate for *k* << 1



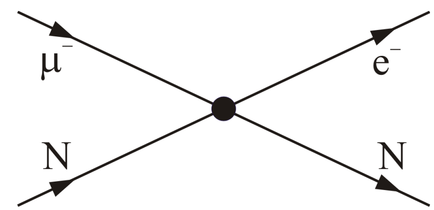
$\mu \rightarrow e\gamma$

$\mu N \rightarrow eN$

$\mu \rightarrow eee$



Contact terms dominate for *k* >> 1



$\cancel{\mu \rightarrow e\gamma}$

$\mu N \rightarrow eN$

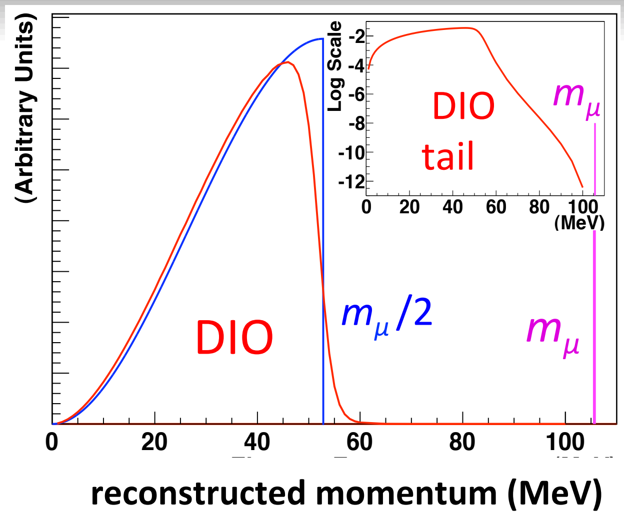
$\mu \rightarrow eee$

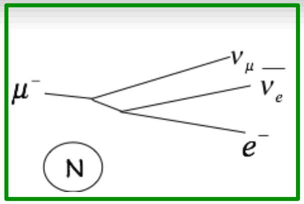
Physics backgrounds

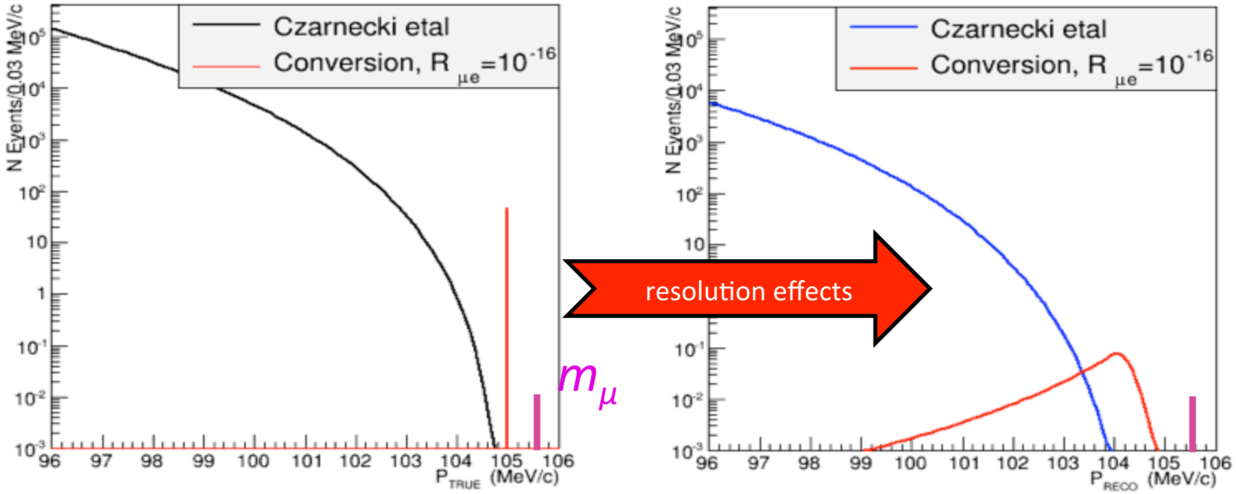
Background	Rejection method
Electrons from muon decay-in-orbit (DIO)	***Good momentum and energy resolution***
Cosmic induced background	***Cosmic ray veto and PID***
Antiproton induced background	***Anti-proton absorber in the TS***
Radiative pion capture and muon decay-in-flight	***Pulsed beam and delayed time signal window***

The dominant background: muon decay in orbit (DIO)

- The tail of the DIOs falls as $(E_{\text{Endpoint}} - E_e)^5$
- Separation of a few hundred keV for $BR_{\mu e} = 10^{-16}$







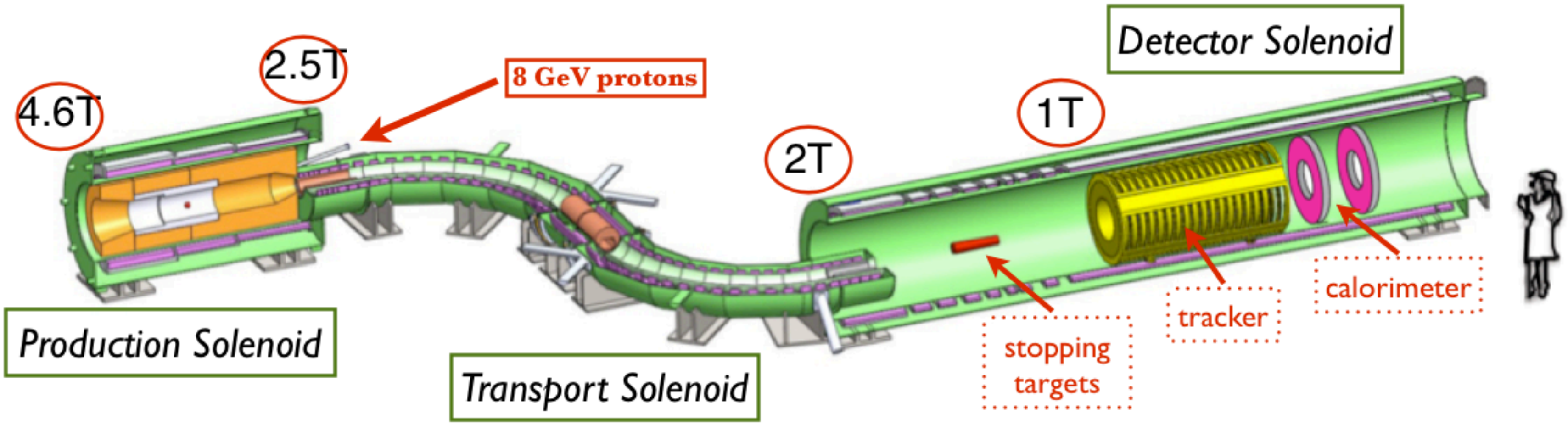
Resolution effects extend the DIO endpoint into the signal region

Czarnecki, Tormo, Marciano, Phys.Rev. D84, 013006, 2011)

The Mu2e experiment layout

• *Production Solenoid:*
➡ Proton beam strikes target, producing mostly pions
➡ Graded magnetic field contains backwards pions/ muons and reflects slow forward pions/muons

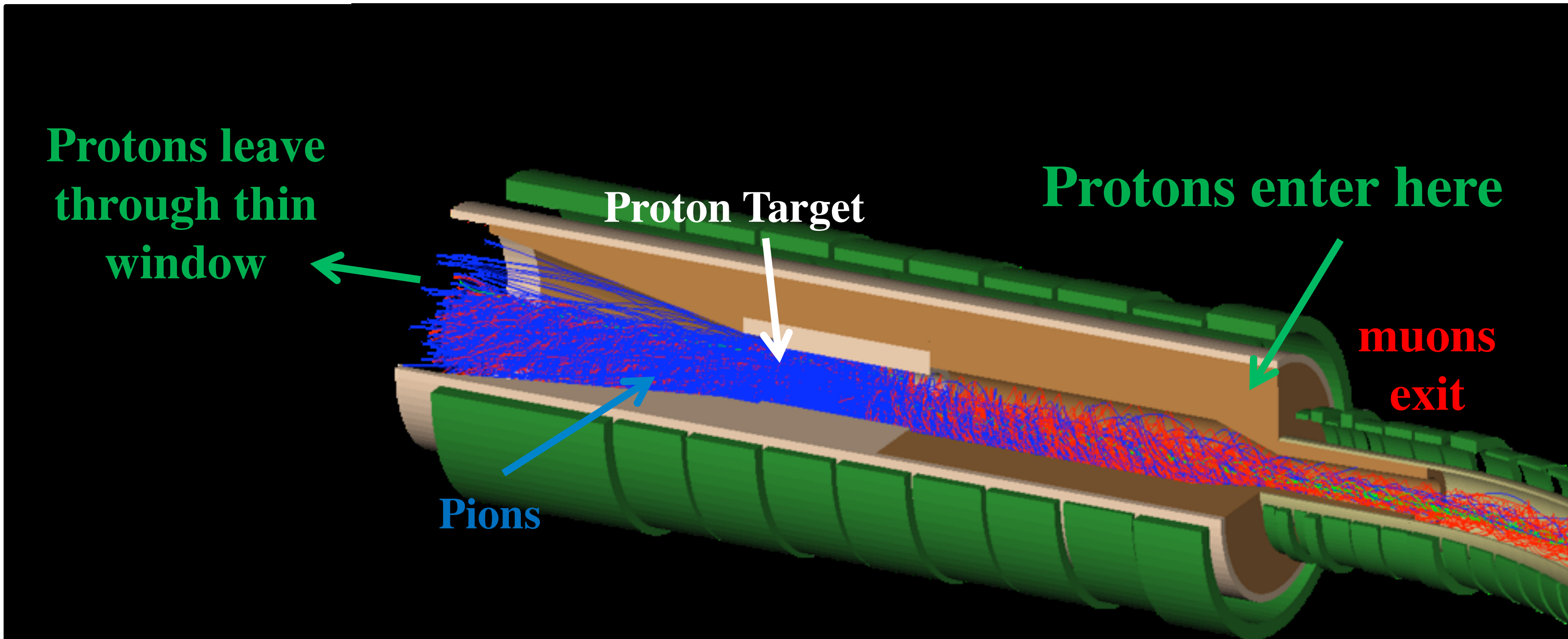
• *Detector Solenoid:*
➡ Capture muons on Al target
➡ Measure momentum in tracker and energy in calorimeter
➡ Graded field "reflects" downstream conversion electrons emitted upstream



• *Transport Solenoid:*
➡ Select low momentum, negative muons
➡ Antiproton absorber in the mid-section

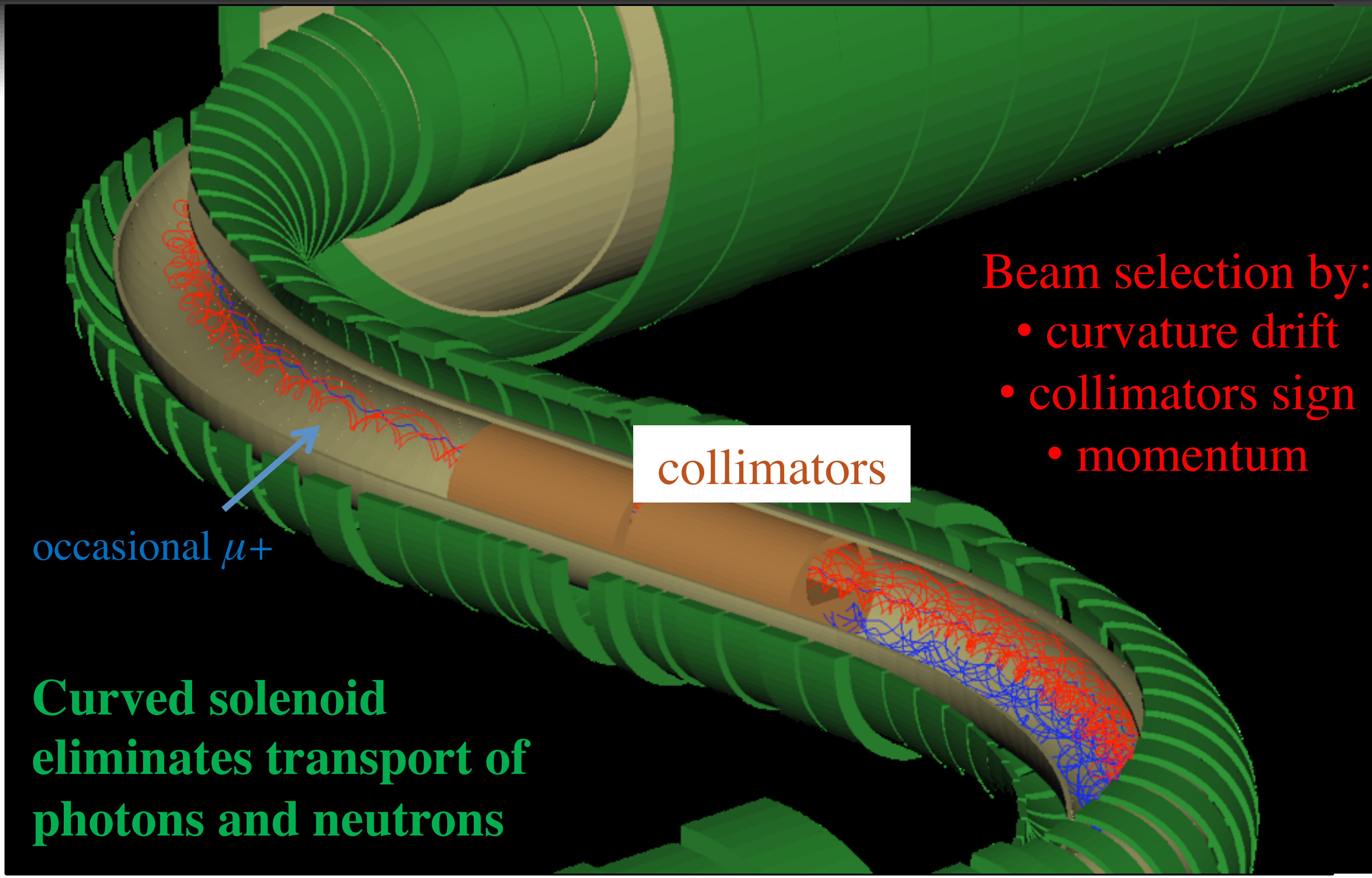
Production Solenoid

Protons enter opposite to outgoing muons:
This is a central idea to remove prompt background



The magnetic field is graded from approximately 5.0 Tesla on the upstream side down to 2.5 Tesla at the entrance to the Transport Solenoid. This graded field captures pions, which spiral around in the field and decay into muons.

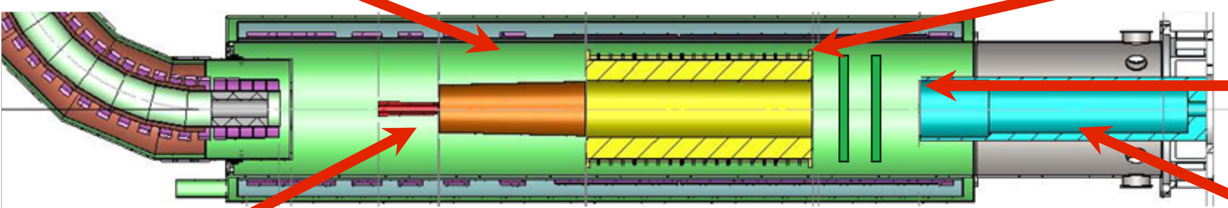
Transport Solenoid



Detector Region

- *Proton absorber:*
  - made of high-density polyethylene
  - designed in order to reduce proton flux on the tracker and minimize energy loss

- *Tracker:*
  - ~25000 tubes arranged in planes on stations, the tracker has 22 stations
  - Expected momentum resolution ~ 120 keV/c



- *Calorimeter:*
  - 2 disks composed of BaF2 crystals and separated by 1/2 wavelength

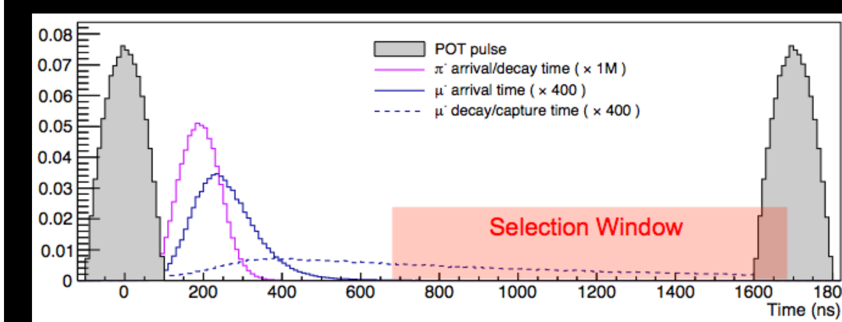
- *Targets:*
  - 17 Al foils; Aluminum was selected mainly for the muon lifetime in capture events (**864 ns**) that matches nicely the need of prompt separation in the Mu2e beam structure.

- *Muon beam stop:*
  - made of several cylinders of different materials: stainless steel, lead and high density polyethylene

choose Z based on tradeoff between rate and lifetime:
longer lived reduces prompt backgrounds

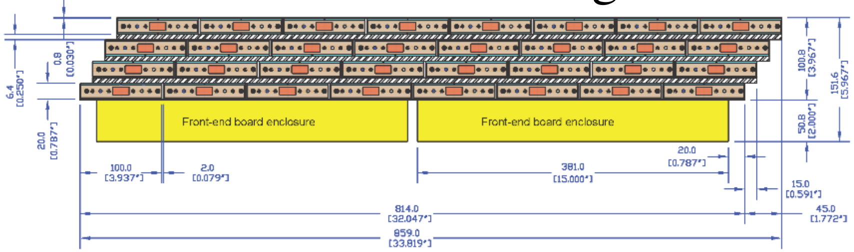
Nucleus	$R_{\mu e}(Z)$ / $R_{\mu e}(Al)$	Bound Lifetime	Conversion Energy	Fraction >700 ns
Al(13,27)	1.0	864 nsec	104.96 MeV	0.45
Ti(22,~48)	1.7	328 nsec	104.18 MeV	0.16
Au (79,~197)	~0.8-1.5	72.6 nsec	95.56 MeV	negligible

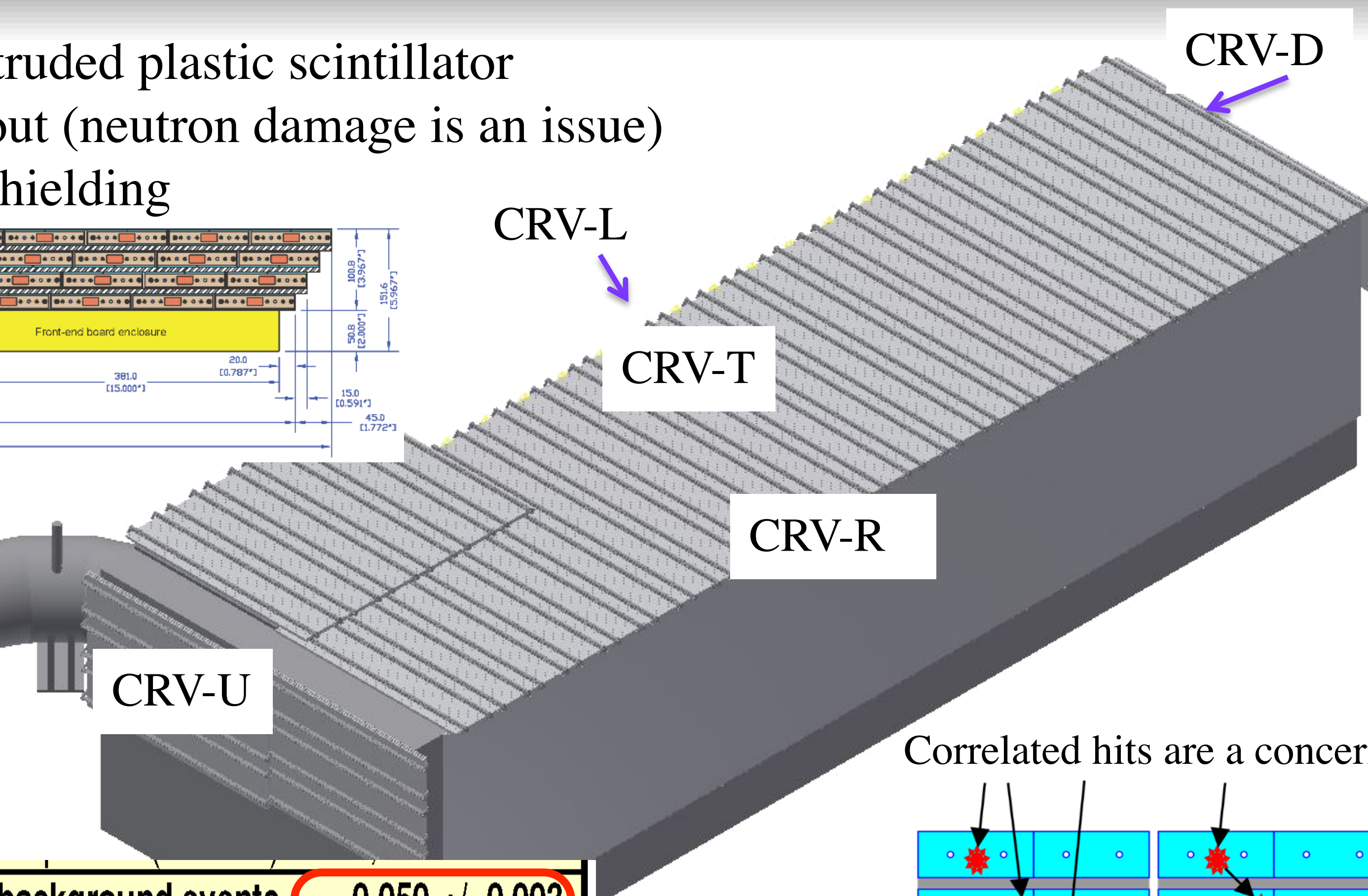
Beam structure



Detector solenoid is surrounded by a cosmic ray veto (CRV)

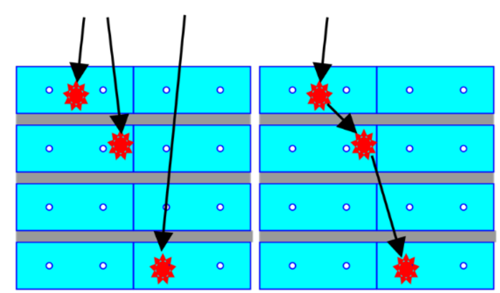
- Four layers of extruded plastic scintillator
- Fiber/SiPM readout (neutron damage is an issue)
- Al and concrete shielding





Desired number of background events	0.050 +/- 0.003
Required CR veto inefficiency	4.11E-05
90% CL CR veto inefficiency	3.83E-05

Correlated hits are a concern

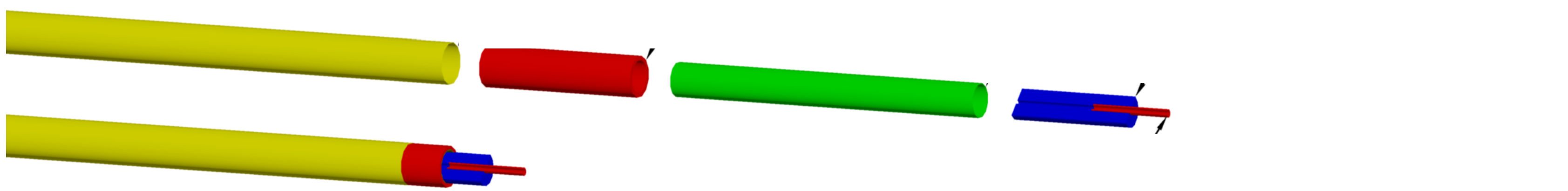


Tracker: straw tubes operating in vacuum -1-

1

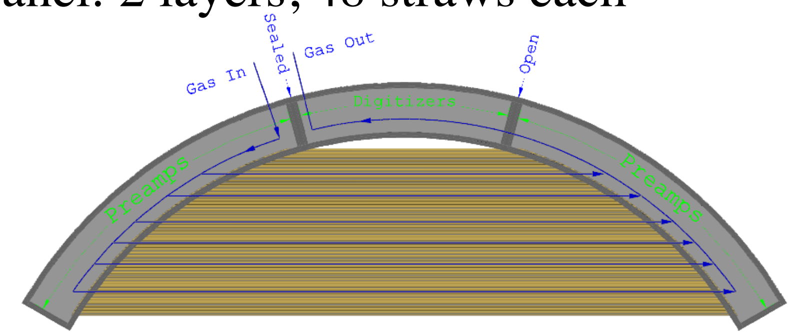
Straws: 5 mm OD; 15 μm metalized mylar wall.

Custom ASIC for time division: $\sigma \approx 5$ mm at straw center



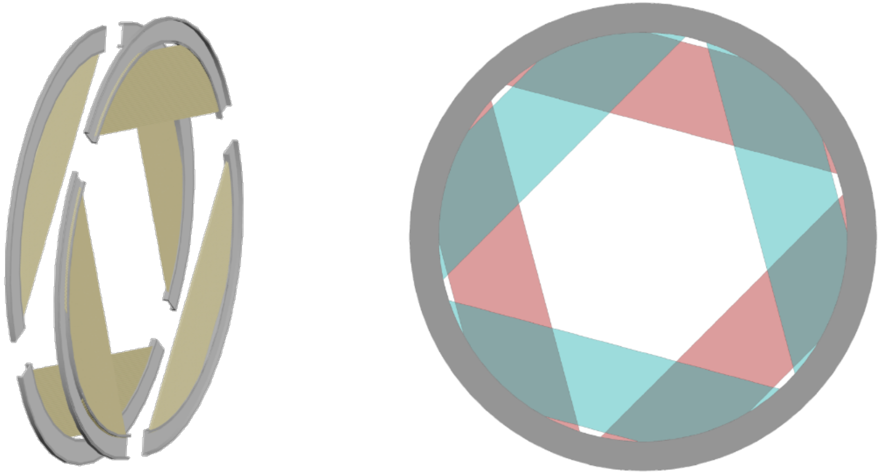
2

Panel: 2 layers, 48 straws each



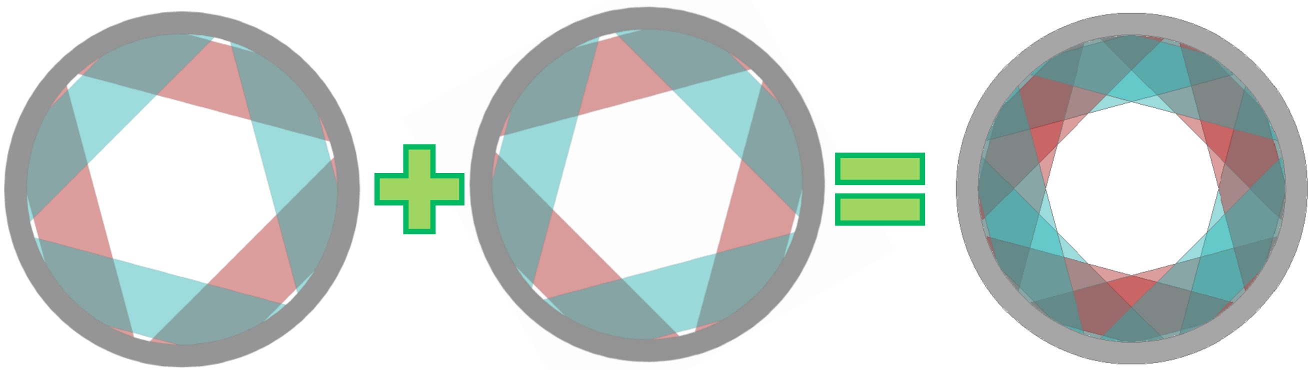
3

Plane: 6 self supporting panels

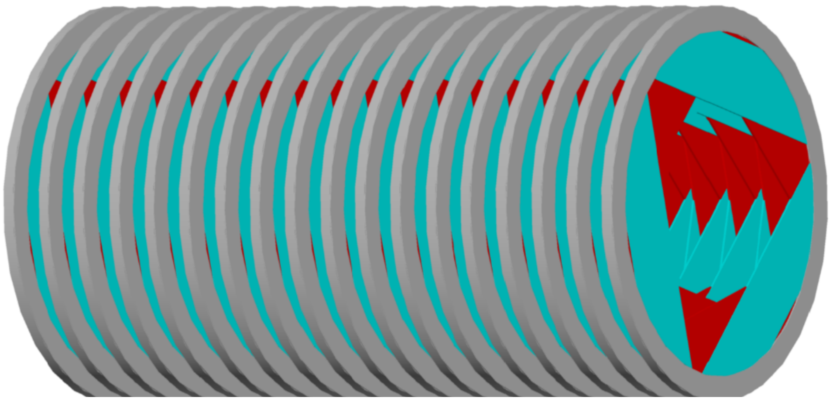


Tracker: straw tubes operating in vacuum -2-

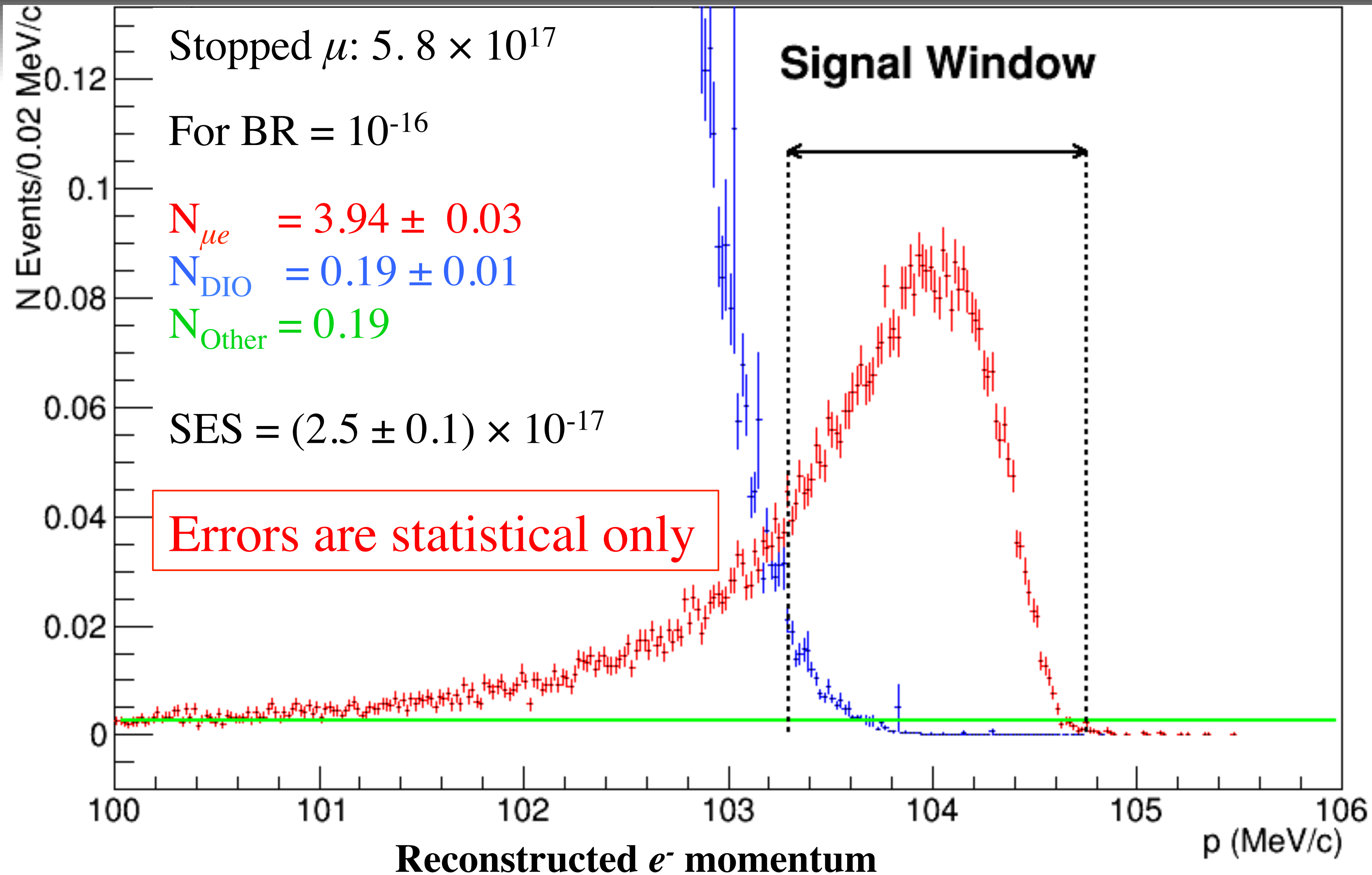
4 Station: 2 planes; relative rotation under study



5 Tracker: 22 stations (# and rotations still being optimized)



Signal sensitivity for a 3 Year Run



Backgrounds for a 3 Year Run

Source	**Events**	**Comment**
DIO	0.20 ± 0.06	
Anti-proton capture	0.10 ± 0.06	
Radiative π- capture*	0.04 ± 0.02	from protons during detection time
Beam electrons*	0.001 ± 0.001	
μ decay in flight*	0.010 ± 0.005	with e- scatter in target
Cosmic ray induced	0.050 ± 0.013	assumes 10^{-4} veto inefficiency
Total	0.4 ± 0.1	

All values preliminary; some are statistical error only.

* scales with extinction: values in table assume extinction = 10^{-10}

The Mu2e Collaboration

Boston University
Brookhaven National Laboratory
University of California, Berkeley and
Lawrence Berkeley National Laboratory
University of California, Irvine
California Institute of Technology
City University of New York
Duke University
Fermilab
University of Houston
University of Illinois, Urbana-Champaign
Lewis University
University of Massachusetts, Amherst
Muons, Inc.
Northern Illinois University
Northwestern University
Pacific Northwest National Laboratory
Purdue University
Rice University
University of Virginia
University of Washington, Seattle

Laboratori Nazionale di Frascati
INFN Genova
INFN Lecce and Università del Salento
Istituto G. Marconi Roma
INFN Pisa
Universita di Udine and INFN Trieste/Udine

JINR, Dubna
Institute for Nuclear Research, Moscow

http://mu2e.fnal.gov

135 members from 28 institutions

The Italian Groups

The Italian Groups are involved in:

Transport Solenoid

E.M Calorimeter

Calorimeter requirements

- Provide a quality check on the reconstructed track measuring:

✓ energy with a resolution of O(5 MeV)

✓ time with a resolution ≤ 0.5 ns

✓ impact position with a resolution ~ 1 cm

- Helpful tool to perform the pattern recognition of tracks
- Particle identification: muon rejection factor > 100
- Filter the events down to a rate ~ few kHz

Survive in the Mu2e environment:

✦ Operable in 1 T magnetic field

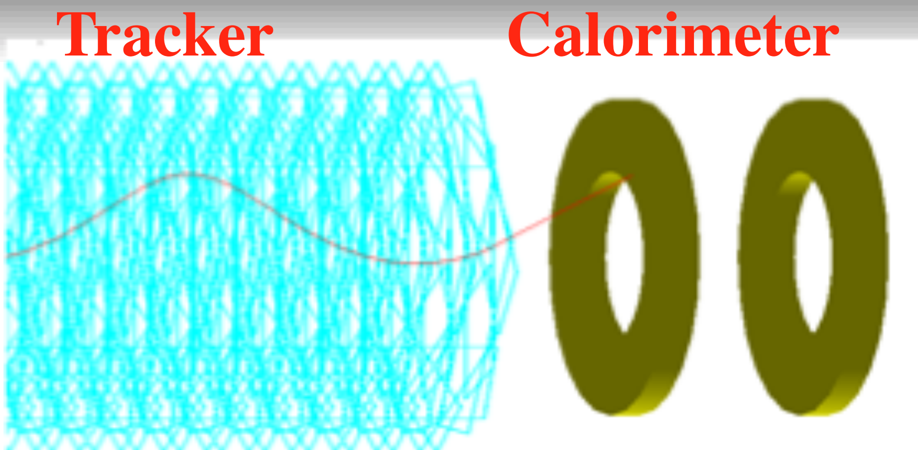
✦ Radiation hard (~ 10 kRad/year/crystal)

Calorimeter crystal history

- Initial choice PbWO4: small X_0, low light yield, low temperature operation, temperature and rate dependence of light output
- CDR choice LYSO: small X_0, high light yield, expensive (→very expensive)
- TDR choice: BaF_2: larger X_0, lower light yield (in the UV), very fast component at 220 nm, readout R&D required, cheaper,

Crystal	**BaF_2**	**LYSO**	**$PbWO_4$**
Density (g/cm^3)	4.89	7.28	8.28
Radiation length (cm) X_0	2.03	1.14	0.9
Molière radius (cm) Rm	3.10	2.07	2.0
Interaction length (cm)	30.7	20.9	20.7
dE/dx (MeV/cm)	6.5	10.0	13.0
Refractive Index at λ_{max}	1.50	1.82	2.20
Peak luminescence (nm)	220, 300	402	420
Decay time τ (ns)	0.9, 650	40	30, 10
Light yield (compared to NaI(Tl)) (%)	4.1, 36	85	0.3, 0.1
Light yield variation with temperature(% / °C)	0.1, -1.9	-0.2	-2.5
Hygroscopicity	None	None	None

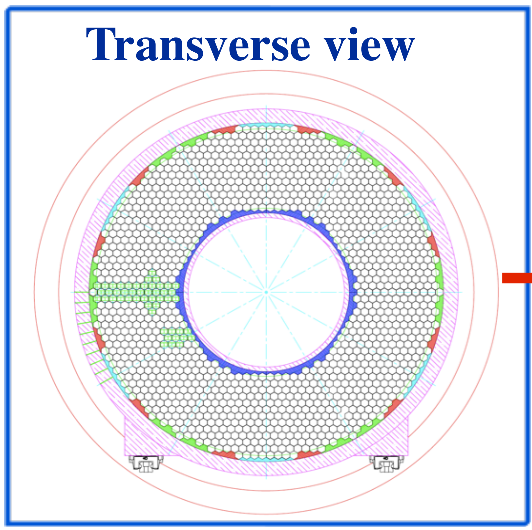
Scintillating crystal calorimeter

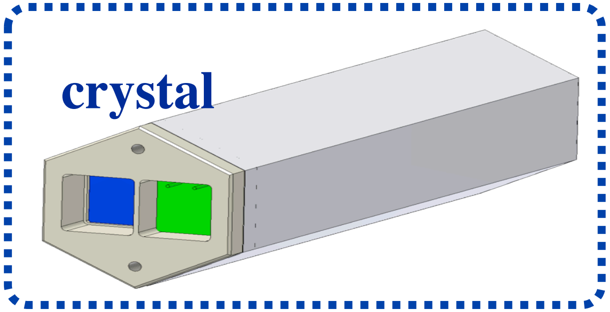


✓ The baseline design consists of two disks; each disk contains 930 hexagonal BaF_2 crystals

✓Disk separation ~ 70 cm

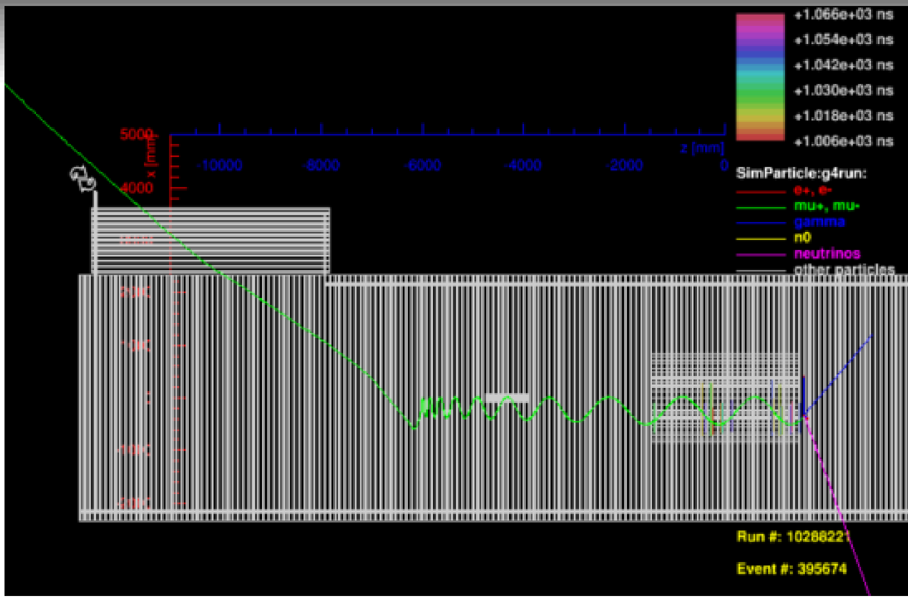
✓ Inner/outer radii: 35.1/66 cm



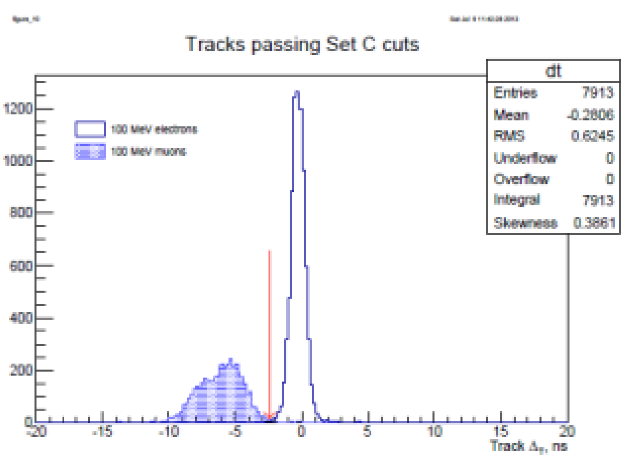


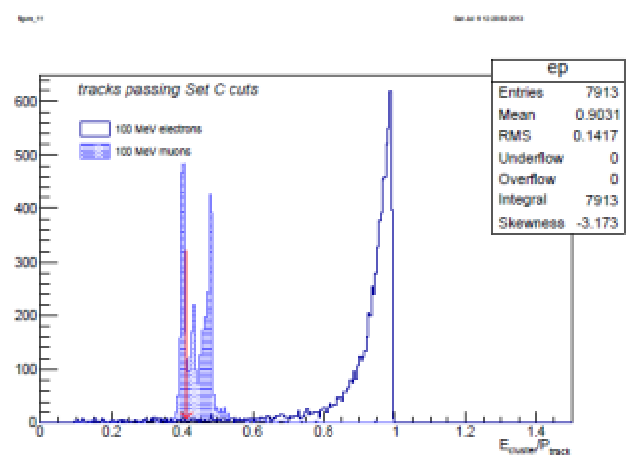
✓ Hexagonal crystals 20 cm length, 3.3 cm face-to-face
✓ 2 APD's/crystal used as readout

The “Ralf event”



- In massive MC runs to optimize the CRV, an event was found that evaded the CRV, passed through the target and the tracker, and stopped in the calorimeter
- The calorimeter, however, provides substantial additional background rejection, through μ/e PID, with a combination of timing information and E/p





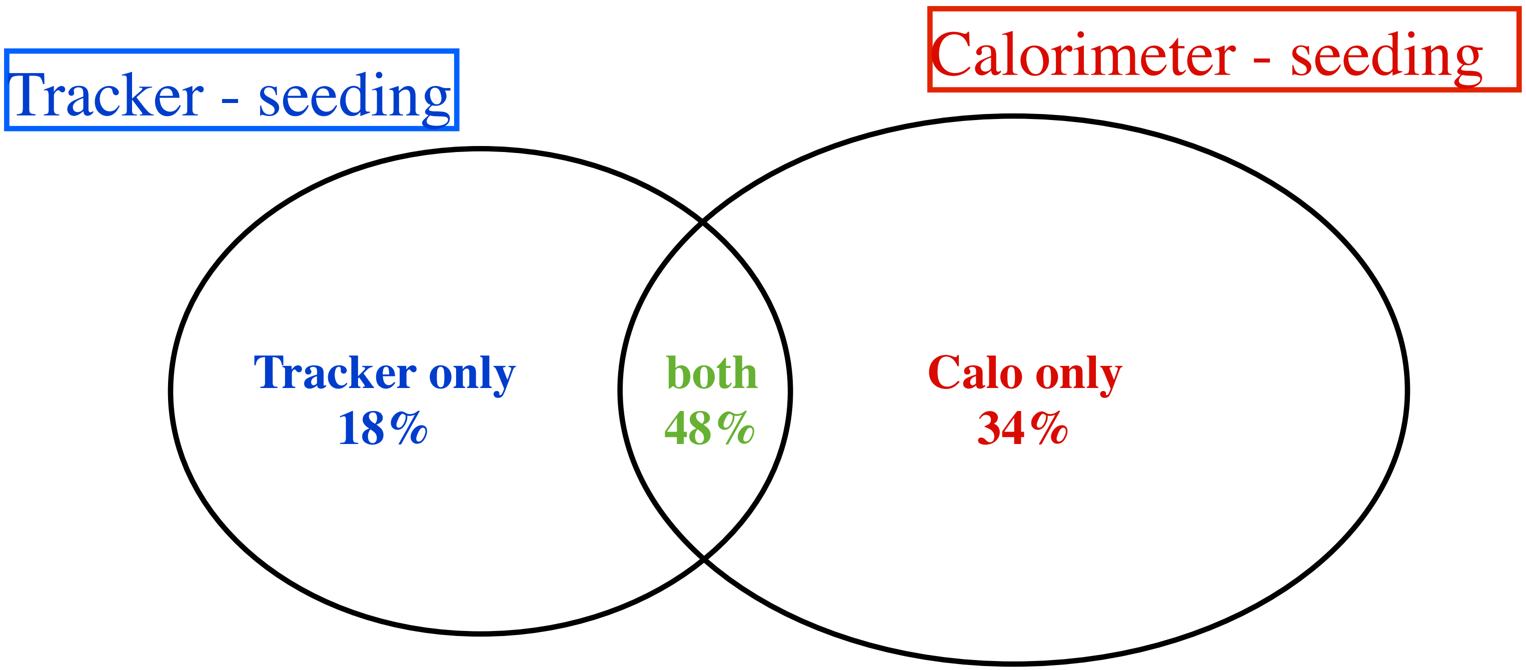
Calorimeter timing and energy deposition provide excellent muon rejection:

$$\varepsilon > 99\%,$$

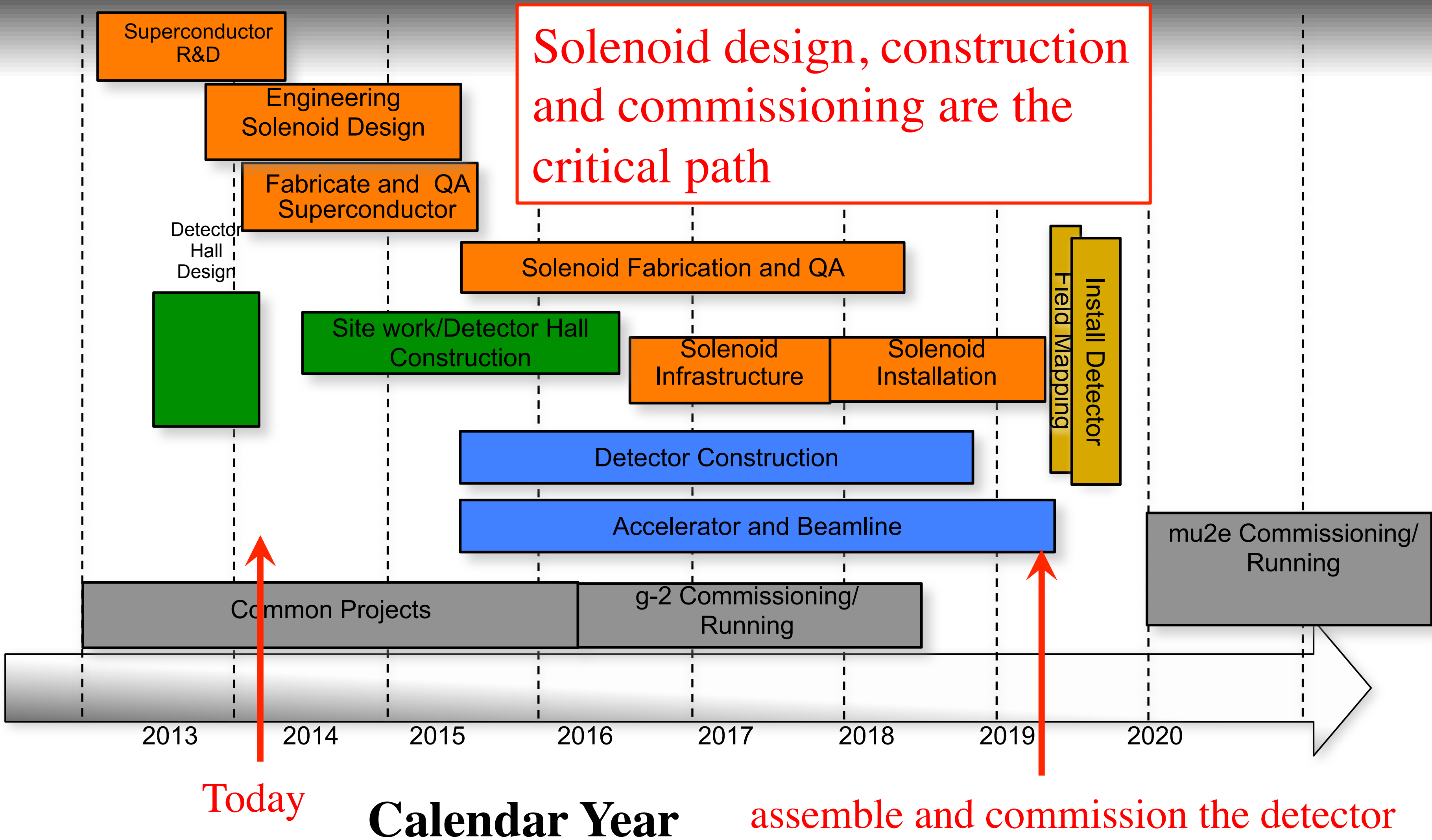
muon rejection ~ 200.

Cal-track Pattern recognition

- Finding the tracks with a calorimeter based technique using only tracker hits passing the requirements on time and the impact position on the calorimeter
- Calorimeter-based approach **adds > 30%!**



Mu2e schedule



Summary and conclusions

- Mu2e will either discover μ to e conversion or set a greatly improved limit
  - $BR_{\mu e} < 6 \times 10^{-17}$ @ 90% CL.
  - 10^4 improvement over previous best limit
  - Mass scales to O(10^4 TeV) are within reach
- Schedule:
  - Final review ~May 2014; expect approval ~July 2014
  - Construction start fall 2015
  - Installation and commissioning in 2019
  - Solenoid system is the critical path
- Mu2e is a program:
  - If there is a signal we will study the A,Z dependence of $BR_{\mu e}$
  - If there is no signal we will be able to improve the experimental sensitivity up to a factor of 10

SPARES

Muonic Atom

• Quando un muone con carica negativa si arresta all'interno di un materiale, viene attratto dal nucleo di un atomo, e rapidamente viene catturato. Successivamente, la particella scendera' attraverso i vari livelli energetici fino a giungere al livello ad energia minima, chiamato *1S*. L'energia emessa durante questo processo, chiamato *cascata muonica*, porterà all'emissione di raggi X, ma i dettagli dell'emissione dipendono dalla natura chimica e fisica del materiale assorbente.

• Dato che la massa del muone è molto maggiore di quella dell'elettrone, la sua orbita sarà molto più vicina al nucleo che non quella di un elettrone: nello stato 1S il raggio orbitale sarà sicuramente confrontabile col raggio di distribuzione di carica nucleare.

• Pertanto, esisterà una certa probabilità che il muone venga catturato da un protone del nucleo. L'atomo tornerà stabile attraverso decadimento beta del neutrone

$$\mu^- + (A, Z) \to \nu_\mu + (A, Z-1)^*$$

$$(A, Z-1)^* \xrightarrow{beta} (A, Z) + e^- \overline{\nu}_e$$

Emits X-rays on the way down:

• •

66 keV, 3d-2p, intensity 62.5%

347 keV, 2p-1s, intensity 79.7%

How Can We Detect these X-Rays?: Stopping Target Monitor,

Complementarity with the LHC

- If new physics is seen at the LHC
  - Need CLFV measurements (Mu2e and others) to discriminate among interpretations
- If new physics is not seen at the LHC
  - Mu2e has discovery reach to mass scales that are inaccessible to the the LHC